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Heating of Intracluster Gas by Jet Activities of AGN: Is the "Preheating" Scenario Realistic?

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ABSTRACT

We investigate the non-gravitational heating of hot gas in clusters of galaxies (intracluster medium; ICM) on the assumption that the gas is heated well before cluster formation ('preheating'). We examine the jet activities of radio galaxies as the sources of excess energy in ICM, and the deformation of the cosmic microwave background (the Sunyaev-Zel'dovich effect) by hot electrons produced at the jet terminal shocks. We show that the observed excess entropy of ICM and *COBE/FIRAS* upper limit for the Compton y-parameter are compatible with each other only when the heating by the jets occurred at relatively small redshift ($z \lesssim 3$). Since this result contradicts the assumption of 'preheating', it suggests that the heating occurred simultaneously with or after cluster formation.

Subject headings: galaxies:clusters:general–intergalactic medium–galaxies:jets–cosmic microwave background–X-ray:galaxies:clusters

1. Introduction

The departure of the properties of X-ray emitting gas in galaxy clusters (intracluster medium; ICM) from simple scaling relations gives rise to arguments about its thermal history (Kaiser 1986, 1991; Evrad & Henry 1991; Fujita & Takahara 2000). Observed relations between X-ray luminosity and temperature show that from a rich cluster scale to a poor cluster scale, the exponent increases from $L_X \propto T_X^{2-3}$ (e.g. David et al. 1993; Xue & Wu 2000) to $L_X \propto T_X^5$ (Ponman et al. 1996; Xue & Wu 2000), which are much steeper than those obtained by gravitational collapse alone ($L_X \propto T_X^2$). Moreover, the discovery of the excess entropy in poor clusters ("entropy-floor") by Ponman et al. (1999) is presently interpreted as a strong evidence for the existence of non-gravitational heating in the ICM.

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One of the popular scenarios to successfully explain these thermal properties of ICM is a so-called "preheating" scenario (e.g. Tozzi et al. 1999). In this scenario, it is assumed that the proto-ICM is heated *well before* the collapse of clusters, which explains the break in the $L_X - T_X$ relation and the entropy floor as follows. If the virial temperature of a cluster, $T_{\rm vir}$, is much higher than the temperature of the external gas, $T_{\rm ex}$, the external gas accreted by the cluster is heated to $T_{\rm vir}$ by shock waves forming at the collapse, and the scaling relation $L_X \propto T_X^2$ should be satisfied (e.g. Cavaliere, Menci & Tozzi 1998). On the other hand, if $T_{\rm vir}$ is comparable to or smaller than $T_{\rm ex}$, shock waves do not form at the collapse, and the external gas adiabatically accretes onto the cluster. Thus, the gas temperature is determined not only by $T_{\rm vir}$ but also by $T_{\rm ex}$. Several authors have shown that preheating models can reproduce the observational results (e.g. Tozzi et al. 1999), however, the heat source itself and the input epoch have not been identified.

Some authors have investigated the heating by supernovae. However, Valageas & Silk (1999) showed that the energy provided by supernovae cannot raise the entropy of intergalactic medium (IGM) up to the level required by current observations. Moreover, Kravtsov & Yepes (2000) estimated the energy provided by supernovae from the observed metal abundance of ICM and found that the heating by supernovae alone requires unrealistically high efficiency. On the other hand, AGNs may be much more powerful and are, therefore, plausible candidates of heating sources, and thus we focus on AGNs.

As for the input epoch, there have been few concrete arguments except for the ones inherent in models of individual sources. For AGNs, there have been no additional constraints like the metal abundance in the case of supernova heating (Kaiser & Alexander 1999). In this paper, we propose a new approach to study this subject. Preheating sources which are so powerful as to influence the thermal properties of ICM would also deform the spectra of the cosmic microwave background (CMB) via inverse-Compton scattering (Sunyaev-Zel'dovich effect; hereafter SZ). Indeed, it has been shown that the energy supplied by AGN jets could be a significant source of SZ effect (Yamada et al. 1999). If the preheating scenario is correct, then the ICM should have been heated before the collapse of poor clusters. This allows us to obtain a lower limit of the redshift of energy input. On the other hand, if a large amount of hot IGM exists too early, the cumulative SZ effect would break the constraint by *COBE/FIRAS* ($y \lesssim 1.5 \times 10^{-5}$, Fixen et al. 1996). In this paper, we compare the estimated SZ effect and the excess energy induced by cocoons formed by AGN jet activities with the observational constraints, and discuss the validity of the simple preheating scenario.

2. Models

2.1. Cocoon model and the Compton y-parameter

We assume for simplicity that the heating of proto-ICM by jet activities occurred well before cluster formation. The kinetic energy of the jet is transferred to thermal energy of the proto-ICM via thermalization at the shock at the hot spot. The thermalized jet matter expands into the

intergalactic medium (or proto-ICM) surrounding the radio galaxy laterally as well as along the jet axis (Begelman & Cioffi 1989; Nath 1995; Kaiser & Alexander 1997; Yamada et al. 1999). As this hot matter expands supersonically, a hot region surrounded by a shock surface around the radio galaxy is expected to form; hereafter we refer to it as a "cocoon". We briefly summarize the evolution of the cocoon below (see for details, Yamada et al. 1999).

While the jet is active, we can write pressure inside the cocoon as

$$P_c = \left\{ \frac{5}{8} \left[\frac{L_j(\gamma - 1)}{\epsilon_v t^2} \right]^2 \frac{\rho_a^2 P_a}{c_a^2} \sin^2 \phi \right\}^{1/5} , \tag{1}$$

by balancing the shock thrust and ram-pressure of the background matter, and by using Rankine-Hugoniot conditions. In this equation L_j represents the kinetic energy of the jet, $\gamma = 5/3$ is the adiabatic index, ϵ_v is the "volume factor" which describes the shape of the cocoon (compared with a sphere), t is the time elapsed since the ignition of the jet, ϕ is the opening angle of the bow shock ahead of the jet termination spot (see Fig. 1 of Yamada et al. 1999), c_a is the sound speed, ρ_a is the gas density, P_a is the pressure, and the suffix a denotes the ambient matter, respectively. In the derivation of the above equation, we assumed that L_j is time-independent, and is given by the Eddington luminosity of the central black hole which activates the jet. We use the gas density of the background universe as ρ_a. We adopt the black hole mass $M_{\rm BH} = 0.002 M_{\rm sph}$, where $M_{\rm sph}$ is the mass of the spheroidal component of the host galaxy (Magorrian et al. 1998). We can estimate the total thermal energy deposited during the jet active phase as $P_c V = \epsilon_{\rm ff} \times (\gamma - 1) L_j t_{\rm life}$, where V is the volume of the cocoon, $\epsilon_{\rm ff}$ is the thermalization efficiency, and $t_{\rm life}$ is the lifetime of the jet activity. We adopt the standard value for $t_{\rm life}$ (3×10^7 years), and take the thermalization efficiency for a free parameter.

While the jet lifetime is short, the cocoon can stay hot for about its cooling time even after the energy supply stops. This "residual" phase contributes much more strongly to the SZ effect (Yamada et al. 1999). We model the evolution of the cocoon adopting the analogy with the evolution of a supernova remnant (SNR) in interstellar medium. Thus we define the effective lifetime of the cocoon as the time from the death of the jet to the epoch when the expansion time $\tau_{\rm ex} = R_s/v_s$ equals the cooling time behind the shock front, $\tau_{\rm cool}|_{\rm shock}$ (R_s and v_s are the shock radius and the velocity, respectively).

Finally we write the evolution of the internal energy of a single cocoon:

$$P_c V = \begin{cases} \epsilon_{\rm ff} L_j (\gamma - 1)(t - t_{\rm begin}), & t < t_{\rm life}, \\ \epsilon_{\rm ff} L_j (\gamma - 1) t_{\rm life} \times \exp[-(t - t_{\rm life} - t_{\rm begin})/t_r(z)], & t > t_{\rm life}, \end{cases} \tag{2}$$

where t is the cosmological time, $t_{\rm begin}$ is the epoch of jet ignition, and $t_r(z)$ is the effective lifetime at redshift z, respectively. Numerical simulations have shown that, although the thermal energy of a SNR rapidly decreases soon after the radiative phase begins, the cooling time increases as the SNR expands further and about 10% of the initial thermal energy is left behind (Chevalier 1974; Thornton et al. 1998). Thus we keep the total internal energy constant after it drops to 10% of its initial value.

The Compton y-parameter is calculated by integrating the product of total internal energy within a single cocoon and the number of radio galaxies in the line of sight,

$$y \approx \int\int \frac{P_c V}{m_e c^2} \sigma_T n_{\rm RG}(M, z_{\rm coll}) a^3 r^2 dr \frac{1}{R_A^2} dM, \tag{3}$$

where m_e is the electron mass, σ_T is the Thomson scattering cross section, $n_{\rm RG}$ is the comoving number density of radio galaxies, $z_{\rm coll}$ is the typical collapse epoch of host galaxy halos, a is the cosmological scale factor, r is the comoving radial coordinate, R_A is the angular diameter distance, respectively (Yamada et al. 1999). We assume that radio galaxies reside in halos with the mass of $M > 10^{10}\ M_\odot$. We also assume that a fraction of normal galaxies has jet activity, and set the proportional constant to be a canonical value $f_r = 0.01$. We count the number of radio (or normal) galaxies using the Press-Schechter number density ($n_{\rm PS}$), and do not use the luminosity function of radio galaxies; this is because we intend to count up the "residual" cocoons, whose effective lifetime (t_r) is much longer than the synchrotron-decay time. We define the epoch of jet ignition $t_{\rm begin}$ separately from the "typical collapse time" $t_{\rm coll}$ of the dark halo of the host galaxy, at which the variance of density perturbation of scale M, $\left\langle \left(\frac{\delta M}{M}\right)^2 \right\rangle$, is equal to 1.69^2 when $\Omega_0 = 1$. We take $t_{\rm gap} \equiv t_{\rm begin} - t_{\rm coll}$ as a free parameter because of the uncertainty inherent in the jet activation mechanism. The value of $t_{\rm gap}$ varies between 0 (jet ignition coeval with the collapse of the dark halo of its host galaxy) and $\lesssim 10^{10}$ years ($\approx H_0^{-1}$).

2.2. Energy Input into Proto-ICM

It is reasonable to assume that the density of proto-ICM traces that of galaxies before the density perturbation corresponding to a protocluster (δ) goes nonlinear. Thus the local number density of radio galaxies and the gas density of proto-ICM in a proto-cluster region are written as:

$$n_{\rm gal}(M, z) = n_{\rm PS} f_r \left(\frac{a_0}{a}\right)^3 (1+\delta), \tag{4}$$

$$n_{\rm gas}(M, z) = \frac{\rho_{\rm crit}}{\mu m_p} \Omega_b f_c (1+\delta), \tag{5}$$

where a_0 is the present scale factor, $\rho_{\rm crit}$ is the critical density, $\mu = 0.59$ is the mean molecular weight for primordial gas, m_p is the proton mass, and f_c is the fraction of the gas compared with the baryon density Ω_b, respectively.

According to equation (4), the energy density ejected by AGNs into a proto-cluster is given as

$$\epsilon_{\rm tot} = \int_{\rm M_l} f_r n_{\rm PS}(M, z) \cdot P_c V(M, z) \cdot (1+\delta) dM. \tag{6}$$

Hence the energy input per nucleon $E_{\rm input}$ at present ($z = 0$) is

$$E_{\rm input} = \frac{\epsilon_{\rm tot} V_c}{n_{\rm gas} V_c} = \left(\frac{\rho_{\rm crit}}{\mu m_p}\right)^{-1} \frac{1}{\Omega_b f_c} \int_{M_l} n_{\rm PS}(M, 0) f_r \cdot P_c V(M, 0) dM, \tag{7}$$

which measures the additional, non-gravitational heating. Hereafter we assume $f_c = 1$, which is reasonable when the density contrast is in a linear regime.

3. Results

We calculate equations (3) and (7) with various combinations of two parameters $\epsilon_{\rm ff}$ and $t_{\rm gap}$. We adopt the standard cold dark matter cosmology, with $\Omega_0 = 1, h = 0.8$, baryon density $\Omega_b h^2 = 0.0125$, and *COBE* normalization for the density perturbations. In Figure 1 contours of the Compton y-parameter and $E_{\rm input}$ are plotted. X-ray observations show that excess energy via non-gravitational heating is $0.44\pm\ 0.3$ keV per a particle (Lloyd-Davies, Ponman & Cannon 2000). The region where parameter values are consistent with the y-parameter constraint obtained by *COBE*, $y \lesssim 1.5 \times 10^{-5}$ (Fixen et al. 1996), and the energy deduced by Lloyd-Davies et al. (2000) is indicated as a shaded region. As is clearly seen, almost horizontal contours from the y-parameter constraint severely limit the value of $t_{\rm gap}$ to be $\gtrsim 6.3 \times 10^8$ years.

The result that the value of y is almost independent of thermalization efficiency $\epsilon_{\rm ff}$ comes from the weak dependence of the expansion speed on the internal energy in the "Sedov" phase ($v_s \propto E_0^{1/5}$, Shu 1992), which results in the weak dependence of cooling time (effective lifetime of a cocoon) on $\epsilon_{\rm ff}$. On the other hand, contours of $E_{\rm input}$ limit the thermalization efficiency to $\epsilon_{\rm ff} \lesssim 0.4$. The fact that the contours of $E_{\rm input}$ run vertically for small values of $t_{\rm gap}$ reflects the rapid cooling of cocoons at high redshift. When $t_{\rm gap}$ is small, the cooling time of a cocoon is so short that the cocoon energy rapidly reduces to 10% of the energy supplied by the jet; thus $E_{\rm input}$ is simply given by $L_j t_{\rm life} \epsilon_{\rm ff} \times 0.1$ and is proportional to $\epsilon_{\rm ff}$. For late input (large $t_{\rm gap}$) the contours slightly curve to left; this is due to the small number of cocoons that contribute to the heating, which means that a large value of $\epsilon_{\rm ff}$ is needed to gain the same amount of energy. In order to assign $t_{\rm gap}$ and the jet ignition epoch, we plot the corresponding redshift $z_{\rm begin}$ as the function of halo mass in Figure 2. Figure 1 shows that $t_{\rm gap} \gtrsim 6.3 \times 10^8$ years, which means heating of ICM occurred at $z_{\rm begin} \lesssim 3$ (Figure 2). Compared to the halo collapse epoch ($t_{\rm gap} = 0$; solid line), the upper bound is very close to the formation epoch of poor clusters with the mass of $M = 10^{13} - 10^{14} M_\odot$. This suggests that the heating of the ICM occurred simultaneously with or after the collapse of the poor clusters, which contradicts the assumption about the heating epoch inherent in the scenario. In other words, our results bring up a serious question about the genuine preheating model.

4. Discussion and Conclusions

We have proposed a new way to elucidate the thermal history of ICM. We have calculated the Compton y-parameter and the energy ejected into the ICM through AGN jet activities assuming that the non-gravitational heat input by the jets occurred well before cluster formation. Comparing them with observations, we have found that the heat input had *not* occurred at $z \gtrsim 3$. Since

$z \sim 3$ is the typical formation epoch of poor clusters, this is not consistent with the assumption of 'preheating' and suggests that the heat input occurred simultaneously with or after the formation of poor clusters. Considering the wide range dispersion in the formation epochs of poor clusters ($z \lesssim 3$; Lacey & Cole 1993; Kitayama & Suto 1996; Balogh et al. 1999), the scenario of heating coeval with the cluster formation may be more plausible and would be consistent with the dispersions of cluster properties (Fujita & Takahara 2000). Note that if the heating occurred in dense environment like in clusters, the lifetime and filling-factor of cocoons will decrease (Yamada et al. 1999), which may reduce the expected value of the y-parameter well below the observational limit. Valageas & Silk (1999) also estimated the y-parameter for QSO heating, but found a smaller value than ours ($y \lesssim 10^{-6}$). This may be because in their model, the energy injected into IGM by QSOs started to cool immediately after the energy injection, which leads to a smaller y value. On the other hand, in our model, a cocoon remains hot for a long time until the cooling sets in (see §2).

Below we discuss several points which are omitted in our simple model. First, a part of electrons may be accelerated at the terminal shock to become non-thermal populations. The SZ effect concerning these populations was calculated by several authors (see e.g., Birkinshaw 1999; Ensslin & Kaiser 2000), and is shown that the amplitude of the signal is reduced by only a small factor for a fixed total energy of the gas. Thus, we do not think that the results in our paper change significantly. Second, although recent works showed that jet matter is suggested to be electron-positron dominated at least at close to the core (e.g, Wardle et al. 1998), some authors proposed that protons constitute a part of the jet energy (e.g Mannheim 1998). If this is the case, the y value due to the jet matter is accordingly reduced, and the input energy epoch may not be constrained by SZ effect.

Recently, *Chandra* observations found that there is no indication of shocks around several radio galaxies in the center of clusters (McNamara et al. 2000; Fabian et al. 2000). These sources reside in such high pressure regions that the expansion speed of lobes is subsonic (e.g. Fujita 2001). We have considered radio galaxies in proto-ICM which has not fully collapsed to have such high pressure, and then have shown that this assumption is not compatible with observational constraints of y and $E_{\rm input}$. Thus *Chandra* findings do not alter our main conclusion.

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REFERENCES

Balogh, M. L., Babul, A., & Patton, D. R. 1999, MNRAS, 307, 263.

Begelman, M. C., & Cioffi, D. F. 1989, ApJ, 345, L21.

Birkinshaw, M. 1999, Phys. Rept. 310, 97.

Cavaliere, A., Menci, N. & Tozzi, P. 1998, ApJ, 501, 493

Chevalier, R. A. 1974, ApJ, 188, 501.

David, L. P., Slyz, A., Jones, C., Forman, W., Vrtilek, S. D. & Arnaud, K. A. 1993, ApJ, 412, 479

Ensslin, T. A., & Kaiser, C. R. 2000, A&A, 360, 417.

Evrad, A. E., & Henry, J. P. 1991, ApJ, 385, 95.

Fabian, A. C. et al. 2000, MNRAS, 318, L65.

Fixen, C. J., Cheng, E. S., Gales, J. M., Mather, J. C., Shaffer, R. A., & Wright, E. L. 1996, ApJ, 473, 576.

Fujita, Y. 2001, ApJ, Letters, in press. (astro-ph/0102221)

Fujita, Y., & Takahara, F. 2000, ApJ, 536, 523.

Kaiser, C. R., & Alexander, P. 1997, MNRAS, 286, 215.

Kaiser, C. R., & Alexander, P. 1999, MNRAS, 305, 707.

Kaiser, N. 1986, MNRAS, 219, 785.

Kaiser, N. 1991, ApJ, 383, 104.

Kitayama, T., & Suto, Y., 1996, MNRAS, 280, 638.

Kravtsov, A. V., & Yepes, G. 2000, MNRAS, 318, 227.

Lacey, C., & Cole, S. 1993, MNRAS, 262, 627.

Lloyd-Davies, E. J., Ponman, T. J., & Cannon, D. B. 2000, MNRAS, 315, 689

McNamara, B. R. et al. 2000, ApJ, 534, L135.

Magorrian, J. 1998, AJ, 115, 2285.

Mannheim, K. 1998, Science, 279, 684.

Menci, N., & Cavalier, A. 2000, MNRAS, 311, 50.

Nath, B. B. 1995, MNRAS, 274, 208.

Ponman, T. J., Bourner, P. D., Ebeling, H., & Böhringer, H. 1996, MNRAS, 283, 690.

Ponman, T. J., Cannon, D. B., & Navarro, J. F. 1999, Nature, 363, 51.

Shu, F. 1992, "Gas Dynamics" (University Science Books).

Thornton, K., Gaudlitz, M., Janka, H.-TH., & Steinmetz, M. 1998, ApJ, 500, 95.

Tozzi, P., Scharf, C. & Norman, C. 2000, ApJ, 542, 106.

Valageas, P., & Silk, J. 1999, A&A, 350, 725.

Wardle, J. F. C. et al. 1998, Nature, 395, 457.

Xue, Y. & Wu, X. 2000, ApJ, 538, 65

Yamada, M., Sugiyama, N., & Silk, J. 1999, ApJ, 522, 66.

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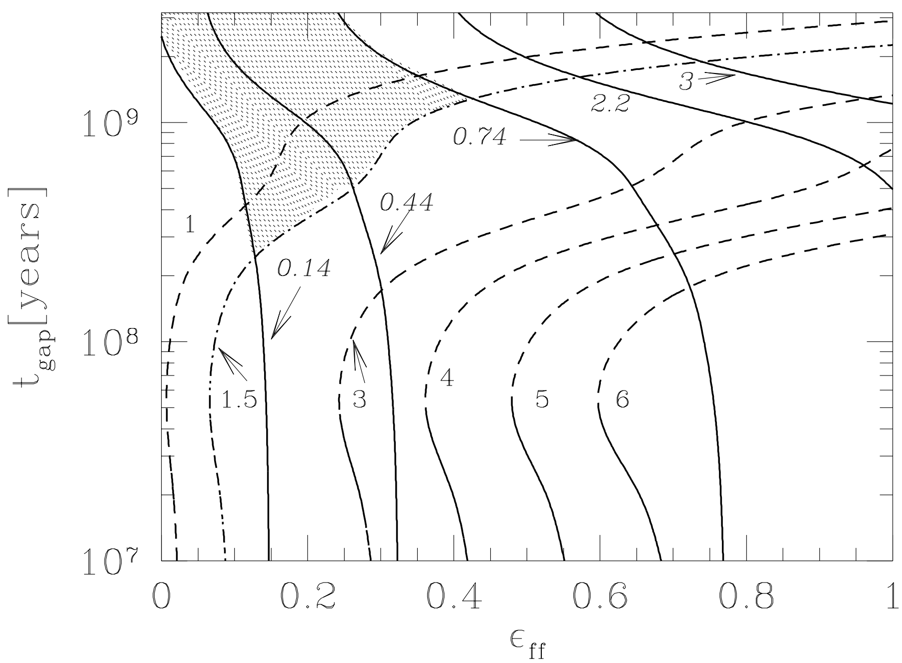

Fig. 1.— A contour map of the Compton y-parameter (dashed lines) and E_{input} (solid lines). Each line corresponds to $y/10^{-5}$=1, 1.5, 3, 4, 5, 6 and E_{input}=0.14, 0.44, 0.74. 2.2, 3 keV, as indicated in the figure. A shaded region is allowed one by *COBE* observation ($y \leq 1.5 \times 10^{-5}$) and by the non-gravitational heating obtained by Lloyd-Davies et al. (2000) (0.44 $\pm$0.3 keV).

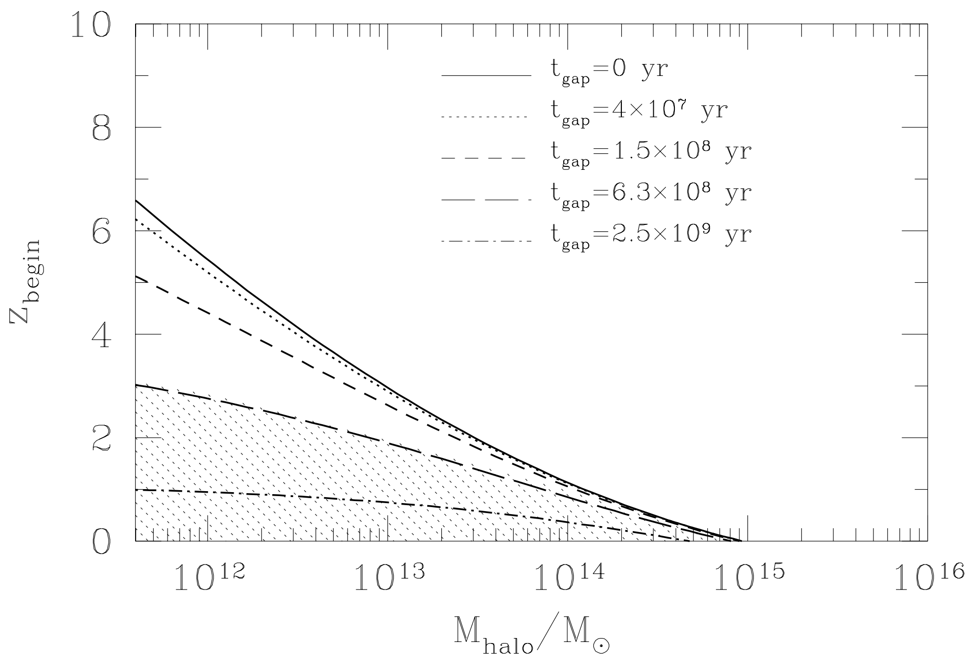

Fig. 2.— Jet ignition epoch as a function of dark halo mass of a radio galaxy with various values of $t_{\rm gap}$. A shaded region corresponds to the allowed value obtained from the Figure 1 ($t_{\rm gap} \gtrsim 6.3 \times 10^8$ years). Solid line ($t_{\rm gap} = 0$) indicates the typical formation epoch of objects of mass $M_{\rm halo}$.